UNIVERSITY OF TECHNOLOGY SYDNEY

Development of a Multi-port DC-DC Converter For a Magnetically-Coupled Residential Micro-grid

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CERTIFICATE OF AUTHORSHIP/ORIGINALITY

I certify that the work in this thesis has not previously been submitted for a degree nor has it been submitted as part of requirements for a degree except as part of the collaborative doctoral degree and/or fully acknowledged within the text.

I also certify that the thesis has been written by me. Any help that I have received in my research work and the preparation of the thesis itself has been acknowledged. In addition, I certify that all information sources and literature used are indicated in the thesis.

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LIST OF SYMBOLS

A_i	Seated area of *i*th component
$h_{\max}$	Height of the highest component
P_{ij}	Transferred power from port *i* to *j*
P_i	Power of port *i*
η_k	Efficiency factor
λ_s	Failure rate of a converter block
λ_j	Component failure rate per million hours
λ_b	Base failure rate of component
π_i	Failure rate modification factor
LT	Life time of component
RF	Reliability factor
$R(ripple)$	Current ripple factor
$X_i(norm)$	Normalized value of the parameter
δ_i	Weighting factor of *i*-th parameter
$I_Q(rms)$	*rms* current in each IGBT switch Q
$I_{fc}(rated)$	Nominal current of the fuel cell port
P_{Q-loss}	Maximum power loss on the switch
ΔI_L	Inductor current ripple
D	Duty cycle
T_s	Switching period
L_C	Critical inductance
r	Ripple ratio
v_i	Voltage of winding *i*

i_i	Current of winding *i*
R_{W_i}	Resistance of *i*-th winding
λ_{ij}	Flux linkage from winding *j* on winding *i*
L_{ij}	Mutual inductance between windings *i* and *j*
L_m	Magnetizing inductance,
R_m	Core loss equivalent resistance
R_w	Winding resistances
Q_{ijk}	3D magnetic element
R_{ijk}	Reluctance of the 3D element
F_{ijk}	Equivalent MMF in 3D element
Φ	Magnetic flow
Vi	Volume of 3D element
L_{eq}	Equivalent inductance
B	Flux density
H	Field intensity
L_{11}, L_{22}, L_{33}	Winding self-inductances
L_{23}, L_{l2}, L_{l3}	Leakage inductances
μ_r	Permeability of magnetic core
N_S	Number of turns of winding
Y'	Central node linked conductance
Y	Source linked conductance
$\widetilde{V}$	Central node voltage
$\widetilde{F}$	Source voltage matrices
W_S	Stored energy in a 3D element
μ	Magnetic permeability
P_v	Magnetic loss density

f	Frequency
B_{sq}	Maximum flux density
Ω	Zero voltage angle
H	Magnetic field intensity
$P_{Cu,n}$	Copper loss due to n-th harmonic of current
$R_{ac,n}$	AC resistance due to n-th harmonic of current
I_n	Peak value of n-th harmonic of current
R_{dc}	Dc resistance of wire
$F_{r,n}$	Ratio of ac to dc resistance
η_{str}	Porosity factor of Litz wire
γ_n	Round conductor penetration ratio
P_f	Packing factor of Litz wire
r_s	Strand radius of Litz wire
r_b	Bundle radius of Litz wire
R_{ins}	Thermal resistance of insulation layer
R_{con}	Convection thermal resistance
h_{rad}	Radiative heat transfer coefficient
P_w	Total heat loss in the winding
l_x	Fraction of the length of a turn in the respective direction x
L_n	Length of a turn of winding
J	Current density
ε	Emissivity of the surface
T_s	Surface temperature
T_a	Ambient temperature
σ	Stefan-Boltzmann's constant
α_n	Phase shift angle
βn	Phase shift angle

φ_{ij}	Phase shift angle of port *i* to *j*
ψ_n	Phase shift angle
υ_{ij}	Dispatch factor
L_{ij}	Leakage inductance between winding *i* and *j*
V_i	DC voltage of port i
V_i	AC voltage of winding i of the magnetic link
V_{bus}	DC bus voltage
φ_B	Boundary phase shift angle
g_{jk}	Gyrator gain in small signal modelling of TAB converter
G_{ij}	Transfer function of input *i* to output *j*
Z_{Chd}	Battery impedance during the charge
Z_{Dsg}	Battery impedance during the discharge
Z_{fc}	Fuel cell equivalent impedance
R_{mpp}	PV panel resistance at maximum power point
$\widetilde{E}_{PV\_24h}(k)$	Predicted 24h-ahead energy generated by PV at the *k*-th sample
$\widetilde{P}_{PV\_24h}(t)$	The forcasted 24 hours-ahead power profile of PV
t_0	Prediction starting time
$\widetilde{E}_{LD\_24h}(k)$	Predicted energy demand of the load at the *k*-th sampling time
T_L	Moving Long time frame
$C_{GD}(n)$	Cost of energy received from or transferred to the grid at the *n*-th sampling time
$C_{FC}(n)$	Fuel cell energy cost
$E_{BT\_24h}^{CHD}$	Energy received by battery in charging mode
$E_{BT\_24h}^{DCH}$	Energy supplied by the battery in discharging mode
$E_{BT\_24h}^{SEL}$	Energy sold to the grid

$E_{BT\_24h}^{BUY}$ Energy supplied by the grid

LIST OF ABBREVIATIONS

A/D	Analogue to Digital Converter
AEMO	Australian Energy Market Operator
BCD	Binary-Coded Decimal
CCM	Continuous Conduction Mode
CCS	Code Composer Studio
CFBC	Current-Fed Boost Converter
CFFB	Current Fed Full Bridge
CFHB	Current-Fed Half Bridge
CHP	Combined Heat and Power
DAB	Dual Active Bridge
DG	Distribution Generation
DSM	Demand Side Management
EMU	Energy Management Unit
EVs	Electric Vehicles
FB	Full Bridge
FCBB	Forward Conducting Bidirectional Blocking
FEA	Finite Element Analysis
FEM	Finite Element Method
FBEMU	Fuzzy Based Energy Management Unit
GEVIC	Green Energy and Vehicle Innovations Centre
GUI	Graphic User Interface
HAM	Home Area Network
HB	Half Bridge
INC	Incremental Conductance
LGEC	Load and Grid Energy Control

MAB	Multi-Active Bridge
μCHP	micro-Combined Heat and Power
MIMO	Multi-Input Multi-Output
MISO	Multi-Input Single-Output
MPC	Multi-Port Converters
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSE	Modified Steinmetz Equation
MTBF	Mean Time Between Failures
MTU	Mode Transition Unit
MWT	Multi-Winding Transformer
NSE	Natural Steinmetz Extension
OSE	Original Steinmetz Equation
PCB	Printed Circuit Board
PCC	Point of Common Coupling
PCSC	Pulsating Current Source Cell
PEM	Proton Exchange Membrane
PI	Proportional-Integral
PL	Positive Large
PS	Positive Small
PLL	Phase-Locked-Loop
PV	Photo Voltaic
PVSC	Pulsating Voltage Source Cell
PWM	Pulse Width Modulation
RES	Residential
RNM	Reluctance Network Model
SIMO	Single-Input Multi-Output

SOC	State Of Charge
SOH	State Of Hydrogen
STD	State Transition Diagram
TAB	Triple Active Bridge
USB	Universal Serial Bus
WAN	Wide Area Network
WCSE	Waveform-Coefficient Steinmetz Equation
ZE	Zero
ZOH	Zero-Order-Hold
ZVS	Zero Voltage Switching

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ABSTRACT

Over the last century, the global average air temperature at the earth surface has been raised for about 0.74°C, which has generated serious concerns all around the world about the global warming and consequent environmental problems. The electricity generation as one of the major contributors to the environmental pollutions should undergo a fundamental change towards the clean energy sources. In the residential sector, one of the major electricity users, the demand for renewable energy sources is increasing significantly.

This thesis presents an effort to develop a residential micro-grid, including multiple renewable energy sources, energy storage, and local loads with multiport power electronic converters capable of bidirectional power flow and intelligent algorithms for power converter and micro-grid controls. A topology of multi-port converter using a high frequency magnetic link is proposed for residential micro-grid applications. Using the magnetic link in the proposed multi-port converter can reduce the complexity and size of the entire micro-grid effectively.

The micro-grid is designed to supply a 4.5 kW residential load from combined energy sources of a PV array, a fuel cell stack, and a battery bank. It is controlled by a Texas instrument DSP (C2000/TMS320F28335) at the device level and a PC system as the energy management unit (EMU) at the system level. A single phase bidirectional inverter is designed to link the proposed micro-gird to the main grid. The inverter is controlled by a second DSP at the device level and by the EMU at the system level.

The proposed micro-grid is able to operate in different operation modes based on the power flow directions and energy management scenarios. The EMU defines the appropriate operation mode of the system based on the short-term and long-term predictions of PV generation, and load demand by changing the power flow directions between the sources, energy storage unit, and loads.

Due to the importance of the magnetic link in the micro-grid performance and complexity of design of high-frequency multi-winding magnetic components, a major part of the research is focused on the design, development and experimental test of the magnetic link. The geometry of the magnetic link including the dimensions of magnetic core and windings are designed through numerical analysis by using the reluctance network model (RNM). The core loss and copper loss analysis of the magnetic link are carried out accurately considering the non-sinusoidal effect of voltage and current waveforms. The designed component is then evaluated for the thermal limits by using the thermal electric model .The last part of this stage is the prototyping, experimental tests, and measurement of the component parameters and performance.

The second part of the research is mainly focused on the design and analysis of the converters as the device level analysis of proposed micro-grid. It contains the analysis of the three dc-dc converters in the steady and transient states, discussion on the modulation technique of each converter, power flow control techniques, small signal modelling, and closed loop control design. The converter steady state waveforms are simulated and the soft-switching operation range is discussed. The converter waveforms are experimentally measured and compared with the numerical simulation results.

The third part of the research is dedicated to the system level control of the micro-grid and energy management analysis. In this section, the main operation modes of the system are defined for both grid-connected and isolated operation conditions according to the power flow directions in the system. An energy management strategy is proposed considering both the short- and long-term energy forecasts and the real-time operational data of the system. The proposed strategy is implemented in an energy management unit using MATLAB/GUI and is used to control the system operation modes considering different control objectives and scenarios.